Novel Penning Ion Trap Designs

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Abstract

Alternative designs for miniature Penning ion traps are presented. An array of traps can be formed simply using long straight wires and this design means that the structure can be miniaturized using well-known techniques. Consequently, these traps should be considered as excellent candidates for applications in quantum information processing. Although the analytical trapping potentials are not exactly quadratic, approximate values for the characteristic frequencies around the equilibrium point can be found. Other viable trap arrays based on multiple pad electrodes are also presented. Although these traps lack the open geometry of the wire traps they may prove useful in a hybrid scheme in which information processing and qubit storage take place in different types of trap. The behaviour of the pad traps is simulated numerically and techniques for moving ions rapidly between traps are discussed.

1 Introduction

The basic principle of an ion trap is very simple: the motion of a charged particle is confined by electric and magnetic fields. Two configurations of three-dimensional ion traps are commonly used: Penning and Paul traps. Typically, both traps consist of a set of three electrodes, a ring electrode and two end-cap electrodes. The Penning trap utilizes an electrostatic potential between the ring and the endcaps in order to confine the ion axially, while a magnetic field provides radial confinement. On the other hand, in the Paul trap a radio frequency (RF) voltage is applied between the endcaps and the ring electrode. This RF component, combined with a constant electrostatic potential, produces axial and radial trapping, see [1]. A large number of variants of these simple traps have been developed including the linear RF trap favoured by groups pursuing quantum information studies with trapped ions.

2 Novel Penning Trap Designs

A new Penning trap design has been proposed recently by Stahl *et al.*[2]. This new trap consists of a planar conducting disk (inner electrode) surrounded by a ring electrode Fig. 1(a). This new concept has many advantages over conventional Penning traps; it presents better scalability and its open geometry allows free optical access to the trapped ions. Stahl *et al.* consider using an array of such traps connected via superconducting wires as the basis of a quantum information processor. In their scheme ion coupling is achieved via image charges induced in the electrodes transmitting signals down the superconducting wires. We consider techniques that allow for a more 'conventional' approach in which ion-ion interactions are mediated by the Coulomb interaction. Scalability is then dependent on following the same strategy as outlined by Monroe *et al.* [3] i.e. a two dimensional array of trapping sites some of which are used for storage and others of which are used for processing. However, moving ions around in a two dimensional array of Penning traps poses its own challenges which we outline below.

3 The planar guide

Based on the same principles and properties as the trap of Stahl *et al.*, an alternative design is presented in this work [4]. Our proposal shares the same open geometry as the proposal by the Mainz group [2] with the benefit that the full equation of motion can be analytically treated. Our proposed trap is made from thin wires or lines of charges and is able to generate an axial potential minimum above the electrodes. At this point the forces acting on a charged particle generated by the two electrodes cancel out; the force coming from a central thin wire is compensated by the force coming from two outer parallel wires, Fig. 1(b). Although this configuration is only able to trap ions along a line above the central wire, a closed loop or the addition of another perpendicular set of wires would be suitable to confine ions in all directions. The advantages of this trap are: it is scalable in a straightforward way, the expression for the electric potential can be analytically solved, and it should be easy to implement in the laboratory.

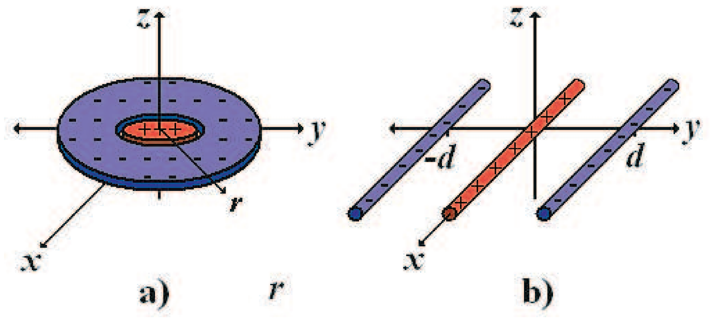

Figure 1 Two planar geometries for ion traps.

The electrostatic potential generated by the geometry presented in Fig. 1(b) is easily calculated using the superposition principle and the well-known potential of a line of charges. This potential is

$$\phi = -\frac{\sigma}{4\pi\epsilon_0}\left(\ln\frac{R^2}{(y+d)^2+z^2} - \ln\frac{R^2}{y^2+z^2} + \ln\frac{R^2}{(y-d)^2+z^2}\right) \quad (1)$$

where σ is the linear charge density, d is the distance between two wires and R is an arbitrary distance at which the potential is set to zero, $R >> d$. The form of the axial normalized potential, for $d = 0.1$ mm and $R = 1$ mm, is presented in Fig. 2.

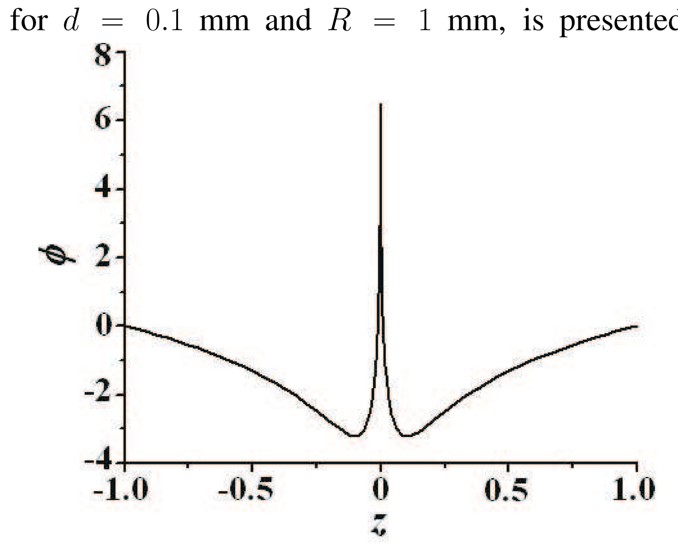
Figure 2 Axial Electrostatic potential, $d = 0.1$ mm and $R = 1$ mm.

If a magnetic field (B) along z is added (as in the Penning trap), the equation of motion is found from the Lorentz force equation. Then, the equation of motion in z is

$$\frac{d^2z'}{dt^2} = -\frac{q\sigma}{\pi m\epsilon_0 d^2}z' \quad (2)$$

where $z' = z \mp d$, q is the charge of the particle and m is the mass of the particle. The axial frequency associated with this harmonic motion is $\omega_z = \sqrt{q\sigma/\pi m\epsilon_0 d^2}$.

These equations represent a circular motion plus a linear drift along x. The electrostatic potential traps axially and the magnetic field confines in one other dimension; the free dimension is the one along the charged lines. Consequently, this can be used as an ion guide because the ion would follow the "path" of the lines. If the guiding wires are given a slight curvature, a closed track would then be able to produce the extra confinement required to trap the ions, Fig. 3.

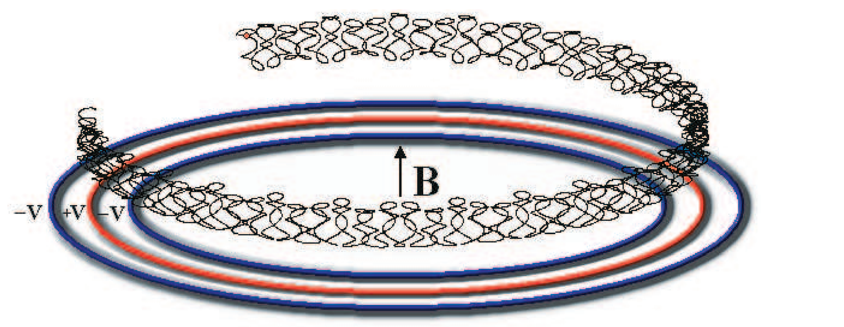
Figure 3 Simulation of the motion of an ion above the ion guide, $B = 0.5$ T, $V_- = -9.28$ V and $V_+ = 2.00$ V.

4 The Wire Trap

The natural next step to generate a three dimensional trapping potential is to try to symmetrize Eq. 1. This is done, by adding to the existing two dimensional potential (in the plane yz) the potential generated in a perpendicular plane (xz) by another set of charged lines parallel to the y axis. The geometry presented in Fig. 4 produces such an effect.

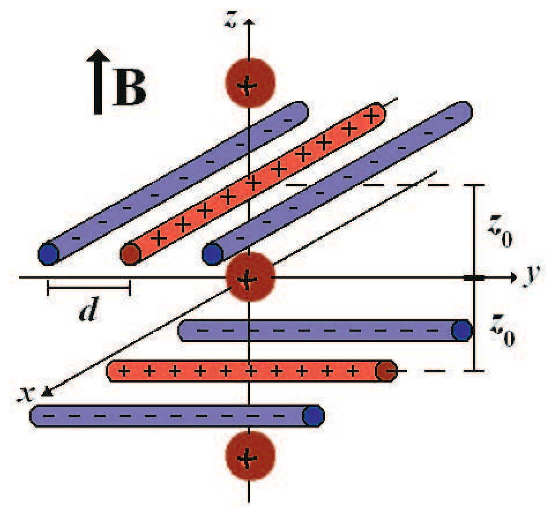
Figure 4 Schematic view of the planar trap, the scale is not preserved.

The potential generated by this geometry can be solved by the superposition of two perpendicular potentials of the form discussed above.

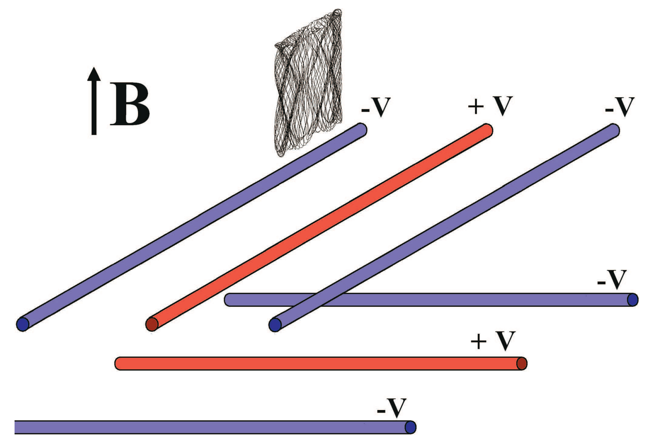
Figure 5 Simulation of the motion of a $^{40}Ca^+$ ion in the trap.

5 Experimental Setup

We have constructed a prototype wire trap shown in Fig. 6. Laser light will enter the trap horizontally and fluorescence will be detected in the vertical direction. We have tested the trap using an electronic detection technique the results of which are shown in Fig. 7. The trap is connected to a resonant circuit and the applied dc trapping potential is scanned so that the axial resonance of the trap passes through the resonance of the circuit. If ions are present in the trap the quality factor of the resonance is modified as the ions absorb energy from the circuit. This manifests itself as the discontinuity in the central curves. The upper (red) curve is the result when the filament that produces ionising electrons is switched off. The lower (violet) curve is the result when the electron filament is on but the oven, producing calcium atoms, is switched off. The middle curve results when both electrons and calcium atoms are present.

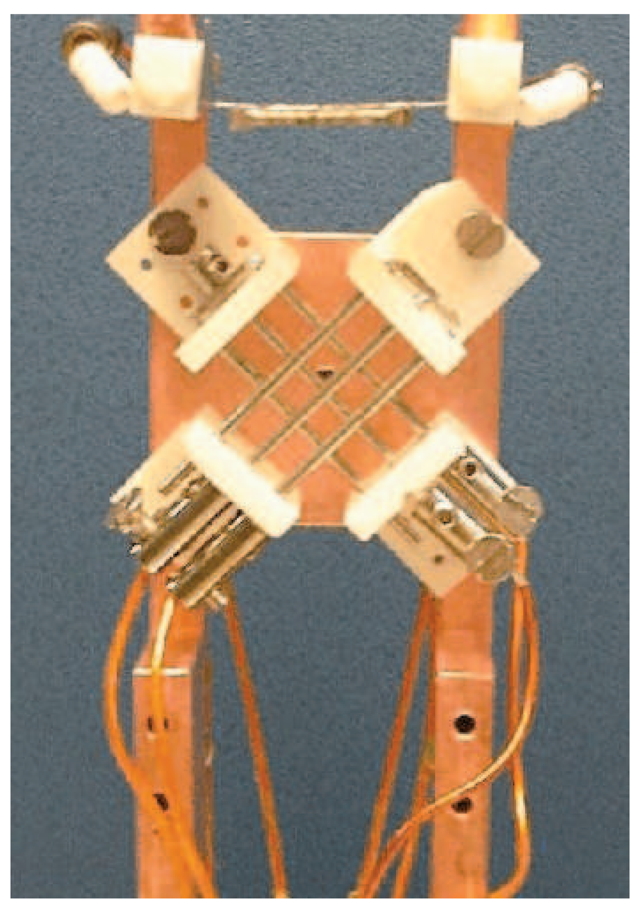
Figure 6 Experimental setup for the planar trap.

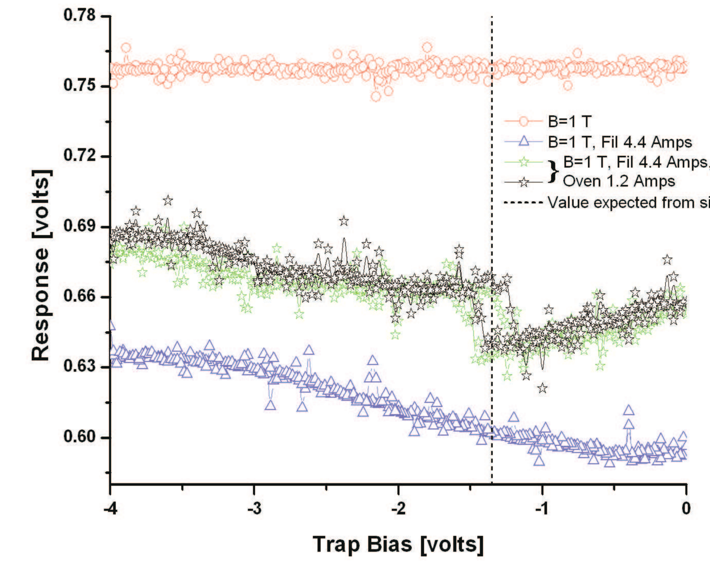

Figure 7 Experimental results of the electronic detection scheme.

5.1 Future Work With Wire Traps

We would like to construct a scalable trap to confine ions in a two dimensional array. This would be a natural extension of our recent work, a schematic view of such configuration is presented in Fig. 8

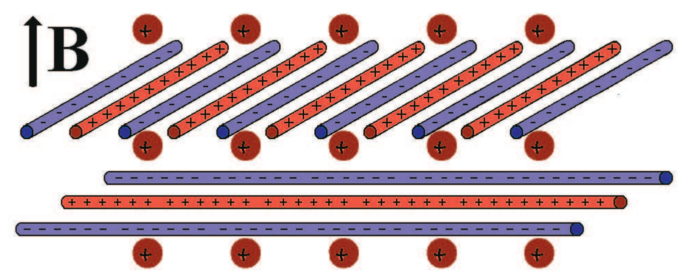
Figure 8 Schematic view of the planar multiple trap.

In addition, we will continue exploring new possibilities to transport ions between traps. Fig. 9 shows a simulation of a guide/trap combined trap. Using the right potentials this design can trap ions or transport them.

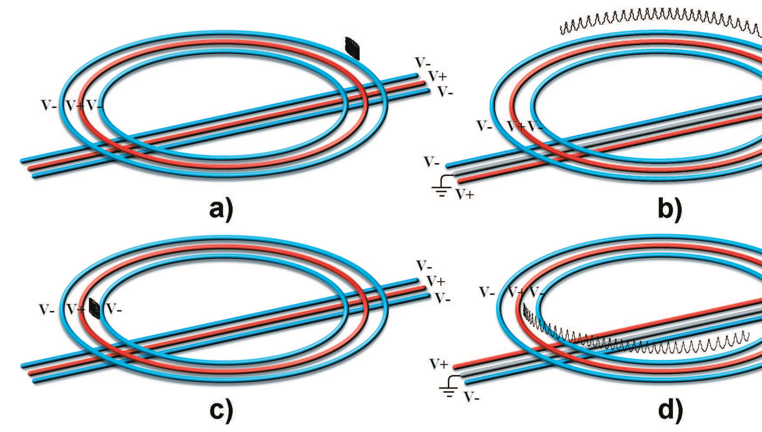

Figure 9 Simulations of a trap design to transport ions.

6 Pad Traps

As we have seen, moving ions in the plane perpendicular to the magnetic field is complicated by the presence of the v × B force. The approach adopted so far is to allow the ion to *drift* in the desired direction (adiabatic approach). Clearly, speed is a concern for QIP so we have also considered a 'diabatic' approach in which an ion is 'hopped' to a desired location in a single cyclotron loop by the application of a pulsed linear electric field. In order to be able to switch between a linear field (for hopping) and a quadrupole potential (for trapping) a different arrangement of electrodes is required. The resulting traps are made up from arrays of pad electrodes whose voltages can be switched rapidly in order to perform the different required operations.

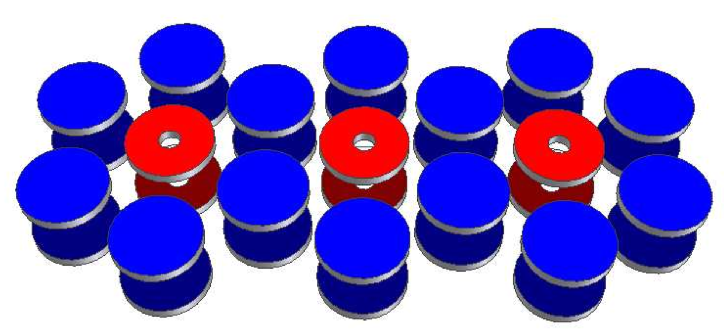
Figure 10. Schematic layout of a pair of pad trap layers. There are three trapping zones, between the three pairs of red (positive) electrodes.

Traps are formed using two arrays of pad electrodes facing each other (Fig. 10). With positive dc voltages applied to the pads at the centres of the hexagonal arrays a set of potentials are generated in the radial plane with near-circular symmetry (Fig. 11(a)).

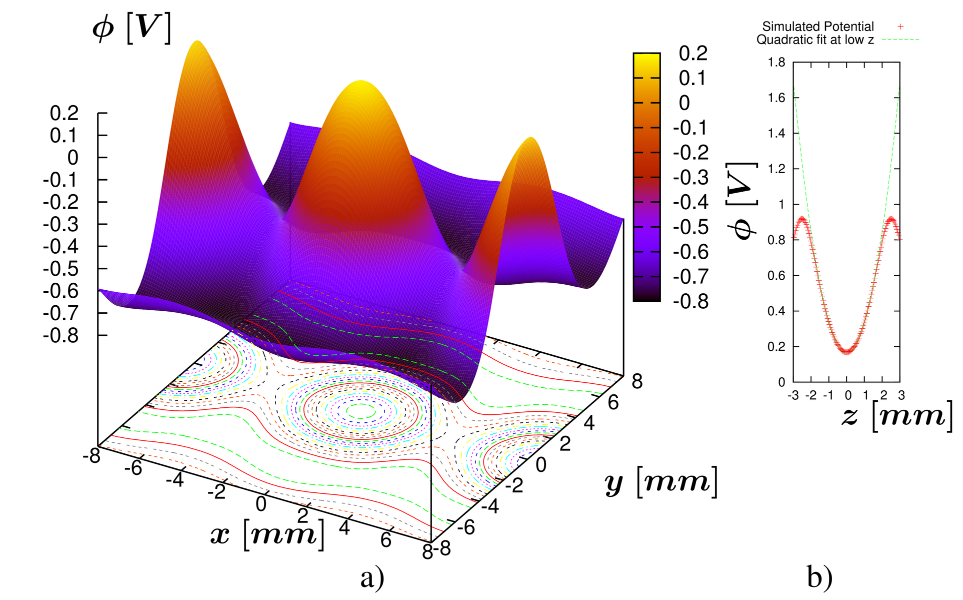

Figure 11. Potential in the plane midway between two pad trap layers, and along the axis of one trapping zone.

Fig. 11 shows the simulated potential for a set of pad traps where each pad is 4mm in diameter, pad centres separated by 5mm. After optimizing the distance between the two pad layers (4.5mm in this case) the potential near the centre is to a good approximation quadratic, ideal for trapping.

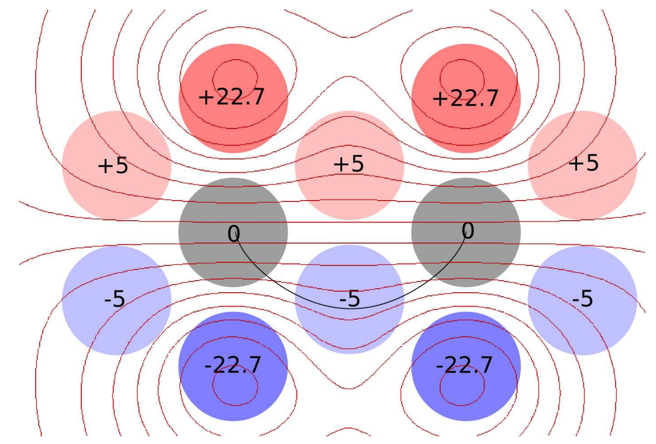

Figure 12. Applying the voltages shown leads to a near-linear electric field in the radial plane. The ion 'hops' from one trap to the other under the influence of the pulsed linear electric field.

Fig. 13 shows the z displacement of a series of ions as they hop from one trapping zone to another. The ions are seen to be confined in the z direction while moving between the traps. The straight lines show the trajectories of particles moving along the z direction in the absence of any fields.

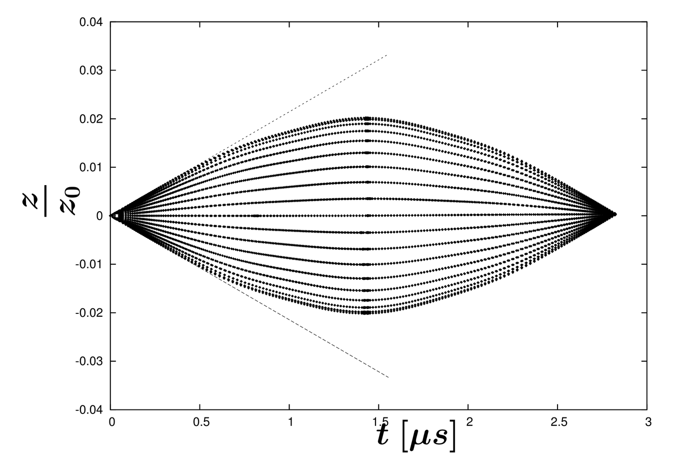
Figure 13. Ions are confined in the z direction as they hop from one site to another.

Pad traps offer the prospect of rapid shifting of ions between traps. There is a price to pay in terms of lack of optical access. If these traps are envisaged as being used for qubit storage rather than for performing gate operations this limitation may be tolerable.

7 References

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8 Acknowledgments

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